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Fractal analysis of calcsilicate bands from Mérida (Spain) contact-metamorphic aureole: implications for fluid flow

J. C. Fernández-Caliani
Dpto. de Geología,
Universidad de Huelva,
Spain

E. Galán
Dpto. de Cristalografía y Mineralogía,
Universidad de Sevilla,
Spain

MANDELBROT'S (1982) considerations about the fractal geometry of nature are being increasingly applied to the Earth Sciences for quantitative description of extremely complex or chaotic structures from a geometric standpoint. Thus, in recent years it has been demonstrated that many natural fracture patterns show fractal geometries (e.g. Korvin, 1992; Turcotte, 1992; and references therein). Accordingly, some geological aspects related to fracturing of rocks are also characterized by their fractal behaviour, such as: epicentre distributions in seismically active fault zones; geomorphology resulting from an intensely fractured massif; ore grade and tonnage of mineralized fracture systems; and spatial and temporal evolution of fluids into fracture-controlled flow zones.

Relating to the last problem, Manning (1994) has shown the fractal clustering of fracture-controlled veins from different metamorphic settings, and consequently he claims that fractal analysis techniques can contribute to the understanding of fluid flow, fluid–rock interaction and mineral reaction during metamorphism.

We present here the results of a preliminary study focused on determining if the spatial distribution of calcsilicate bands embedded in Cambrian marbles from the Mérida (SW Spain) contact-metamorphic aureole (Fig. 1) correspond to the fractal model. The calcsilicate bands formed from channalized infiltration of externally derived H_2O-rich fluids by the reaction of these fluids with calcite along marble-metachert contacts, resulting in very pure wollastonite mineralizations (Fernández-Caliani, 1995). In this case, fractal dimension of the band spacings could be an approach to determining the degree of channalization of the fluid flow and the extent of progress of the wollastonite-forming reaction.

Analytical method

The most important feature of fractal geometry is the invariance over a wide range of scales, which is known as self-similarity. The method used for estimating the scale invariance and the fractal dimension of calcsilicate bands is a one-dimensional analysis based on linear regression of the band-spacings data, that is, a version of the box-counting method (e.g. Chiles, 1988; Walsh and Watterson, 1993; Manning, 1994).

The study area is a well exposed outcrop consisting of carbonaceous marble with abundant interbedded calcsilicate bands showing an apparently random distribution (Fig. 2). The surface was subdivided into equidimensional step intervals of length r, and the number of steps (Nr) that contain at least one calcsilicate band was recorded by counting along a linear transect of 1.5 m length outlined across the outcrop, over a range in r from 1 to 50 cm.

By defining the fractal set, Nr is related to r as follows:

$$Nr = C/r^D$$

where C is a constant of proportionality, and D is the fractal dimension. Thus, in case of self-similarity, a straight-line relation between Nr and 1/r will be

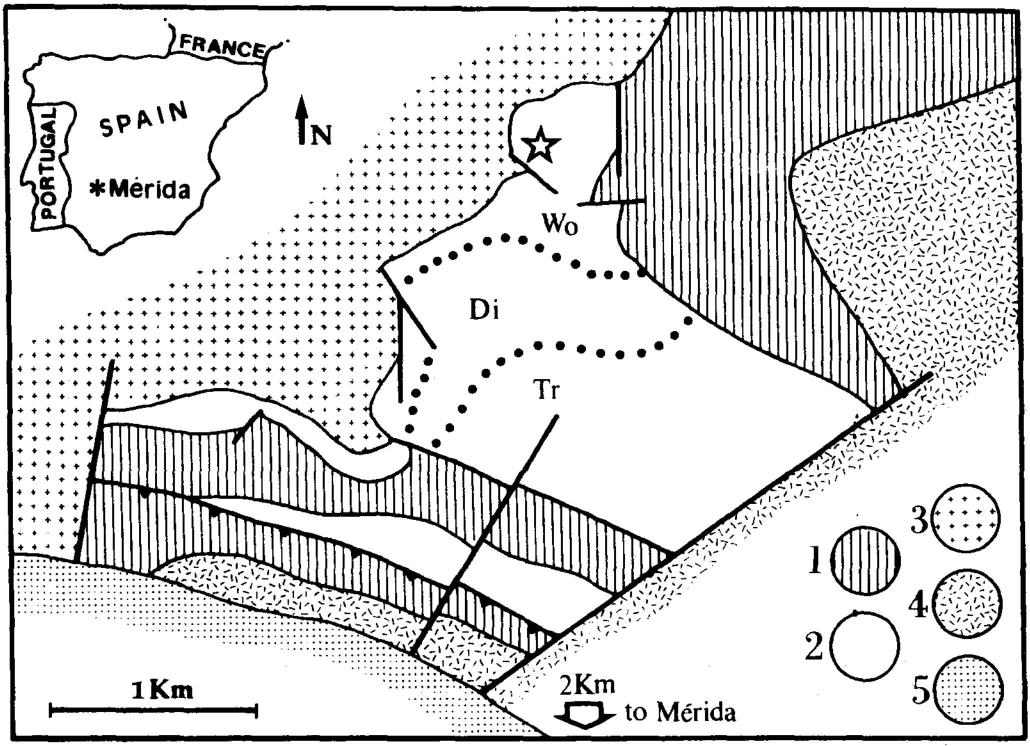

FIG. 1. Geological map of the Mérida contact aureole with three metamorphic zones (Wo: wollastonite zone; Di: diopside zone; and Tr: tremolite zone) mapped on the Carbonate formation (simplified from Fernández-Caliani,1995). Star represents the location of the calcsilicate bands described in the text. (1) Precambrian amphibolite formation; (2) Cambrian carbonate formation; (3) Hercynian granite; (4) Early Hercynian diorite; and (5) Post-Hercynian cover.

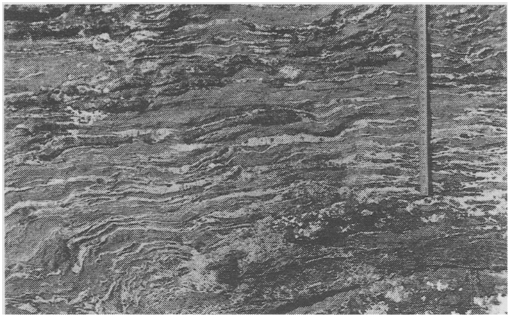

FIG. 2. Field photograph of the calcsilicate bands interbedded into Cambrian marbles from the Mérida contact aureole.

expected with a high linear-regression correlation coefficient (R).

In order to determine D, the aforementioned relation can be written as:

$$\log Nr = \log C - D \log r$$

where the slope is interpreted as fractal dimension.

In this model, intersections of calcsilicate bands with the transect define points on a line, and so values of fractal dimensions will range between 0, if only one band is encountered, and 1 when the plane is completely filled by wollastonite. Therefore, the fractal dimension reflects the degree of space filling, and it allows the quantification of the transition from pervasive flow (high D) to more channelled flow (low D) during metamorphism, in accord with Manning (1994).

Results and metamorphic implications

For the investigated range in r, the spacing of calcsilicate bands shows bilogarithmic distributions that could be interpreted in relation to a fractal clustering. Indeed, Fig. 3A depicts a strong linear correlation between log Nr and log 1/r (R = 0.97), which means that spatial distribution of calcsilicate bands into marbles is statistically self-similar, with a fractal dimension of 0.75.

Nevertheless, a careful examination of the data points on the graph reveals that self-similarity is not preserved over the complete scale of observation, since the plot appears to show a breakpoint separating two linear segments that represent different fractal regimes (Fig. 3B). Thus, regressing the data for each line segment, two distinct fractal dimensions were obtained: At low r – textural domain – calcsilicate bands have a fractal dimension (Dt) of 0.38 whereas at high r – structural domain – the fractal dimension (Ds) is 0.90. Although these domains are characterized by self-similarity over a definable range, the spacing of calcsilicate bands over the whole observational scale is not consistent with the original concept of fractal geometry introduced by Mandelbrot (1967).

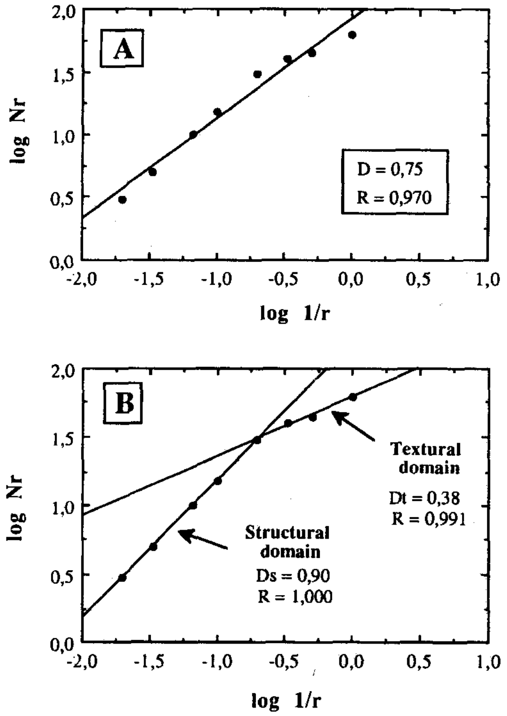

FIG. 3. Plots showing the variation in number of steps (Nr) with log 1/r for spacing of calcsilicate bands. (A) Fractal dimension over the entire scale of observation; (B) Bifractality resulting from division of data points into structural and textural domains.

This bifractality has allowed us to recognize two contrasting fluid flows at different scales. Taking into account the observed values of D, over the great-scale, aqueous fluids emanating from a near granitic intrusion were pervasively distributed in the Mérida contact aureole. By contrast, at smaller scales, the fractal dimension suggests that fluid infiltration was clearly channelled to marble–metachert contacts and fractures, which acted as channelways for migration of fluids during metamorphism, due to low permeability of the marbles.

Conclusions

Since multiple fractal elements have been detected, the spacial distribution of calcsilicate bands into marbles must be referred as *pseudofractal* in the sense of Orford and Whalley (1983). The evolution of fluid flow is scale-dependent, which strongly suggests different fluid-flow models for the two domains investigated.

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